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The Extent, Effects and Management of Forestry-related Soil Disturbance, with Reference to Implications for the Clay Belt:

A Literature Review

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by
Rob Arnup
Ecological Services for Planning

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1.0 Introduction

Forestry activities can lead to soil disturbances that include compaction, rutting, and soil displacement (e.g. mineral soil exposure, erosion, and organic matter reduction). Soil rutting has been a major concern in the Clay Belt on clay and organic soils because of its negative visual image, its association with sites that are wet and difficult to operate on, and because of fears that it is associated with reduced opportunities for regeneration, and reduced productivity. Concerns with erosion are less common in the Clay Belt due to its generally level topography, although concerns arise where mineral soil is exposed adjacent to water courses, with the potential for surface soil movement into the water and subsequent sedimentation. The removal of surface organic layers on clay soils are a known concern in the Clay Belt. Spruce seedling establishment on bare clay soils has met with little success, due to frost heaving, desiccation, and poor root penetration. Soil compaction has also been identified as a concern because of the predicted negative effects on regeneration establishment, growth and yield.

Initiatives related to sustainable forest management in Ontario have underlined the importance of improving our knowledge of soil disturbance relationships. The Crown Forest Sustainability Act provides for "long term health and vigor of Crown forests ... by using forest practices that ... [minimize] adverse effects on plant life, animal life, water, soil, [and] air". Guidelines for the protection of the physical environment for use in Forest Management Planning (Archibald *et al.* 1997) are now available and address best management practices for minimizing soil disturbance.

There is little information available on soil disturbance that is specific to the Clay Belt in northeastern Ontario. To our knowledge, only a single preliminary research study has been conducted on compaction and rutting effects on clay mineral soils (Shurman and Mackintosh 1985). Consequently, a more general review of soil disturbances has been conducted. This report synthesizes:

- information available from the scientific literature on types of soil disturbance, factors affecting soil disturbance, and its biological and physical effects;
- soil engineering and equipment properties related to soil disturbance;
- knowledge of the relationship between changes in soil properties and effects on forest productivity;
- knowledge of factors that ameliorate soil disturbance and associated management practices; and
- implications of this information to Clay Belt conditions, and the extent to which knowledge of soil disturbance can be extrapolated from other jurisdictions.

This information will contribute to the ongoing development and improvement of management practices to minimize soil disturbances in the Clay Belt, including the selection of appropriate forestry equipment.

2.0 Types of Soil Disturbance

Soil disturbance refers to a change in the natural state of a soil caused by an artificially imposed force. For the purpose of this review, forest soil disturbance can be broken down into three categories:

- compaction;
- rutting; and
- soil displacement.

2.1 Compaction

Soil compaction is the increase in soil density that results from the bringing together of soil particles in response to applied external forces. In forestry, compaction can occur as a result of the movement of equipment over the soil. Compaction effects can also occur naturally in soils over longer periods as a result of settlement and slumping, especially at high water contents (Soane 1990). Compaction is a process which leads to an increase in soil density as a result of the application of stresses, usually of short duration, resulting from the passage of machine traffic. Bulk density may be used as an index of relative compaction, but it does not allow an assessment of soil strength, and it is soil strength which determines resistance to compaction (Greacen and Sands 1980).

Susceptibility of forest soils to compaction is influenced by the following factors:

- applied force (e.g. lower equipment ground pressure reduces compaction effects)
- soil texture (e.g. loams are more susceptible than sands or clays)
- soil moisture content at the time of operation (e.g. silts and clays are more susceptible when moist)
- coarse fragment content (stony soils are less susceptible)
- soil structure (e.g. well-structured soils are more resistant to compaction when dry)
- native bulk density and macroporosity (e.g. smaller changes in soils with low macroporosity can have greater relative effects on plant growth)
- native degree of compactness (e.g. soils that are naturally compacted due to their geological origin are resistant to further compaction)
- thickness and nature of the surface organic and root mat layers (these layers, especially fibric materials, protect the underlying mineral soil from compaction)

Each of these factors alone, or in combination, affect the degree of compaction that can result from an applied force on a forest soil. Soil compaction can occur on any site with any type of soil. However, it is generally more severe on sites without a root mat or surface organic matter, with texturally well graded soils (soils with mixed particle sizes, such as loams) that are low in organic matter content, and on moist soils. Although clays are not as susceptible as sands or loams, a lesser level of compaction can have a relatively greater effect on vegetation growth, since the initial macroporosity levels for clays are much lower than other soil types.

Soil compaction, depending on its severity, can have the following effects on soil physical properties:

- increase in bulk density
- decrease in air-filled porosity (especially macropores)
- decrease in water infiltration rates
- decrease in hydraulic conductivity
- increase in heat conductivity and diffusion, resulting in soil temperature changes
- increased depth of freezing
- change in nutrient ion diffusion rates (either increase or decrease)

Soil Bulk Density and Soil Porosity

Soil density is defined as mass per unit volume, and is usually expressed as grams per cubic centimetre (g/cc). The mass of a mineral soil is composed of sand, silt and clay particles, with varying amounts of organic matter. The average density of minerals that commonly make up a soil is approximately 2.60 g/cc, which represents the upper theoretical limit of mineral soil density (Schurman and Mackintosh 1985). The reported upper limit of bulk density for organic soils is 1.50 g/cc (Hassan 1978).

The density of any forest soil is always less than the theoretical maximum, due to air spaces (soil

pores) which occupy the volume between the solid particles. For example, measurements of organic peat soils indicated that natural bulk density varies from 0.02 g /cc for samples of Von Post 1 (fibric) up to 0.98 g/cc for samples of Von Post 8 (humic).

Soil bulk density provides a measure of the amount of pore space in the soil. For example, if the bulk density of a soil is measured as 1.30 g/cc, then the total pore space (porosity) available for air and water is 50 percent (i.e. [2.60 - 1.30] / 2.60 x 100 = 50 percent). Table 1 illustrates typical soil porosity levels (expressed as a percent of total soil volume) for selected bulk densities for both mineral and organic soils.

The distribution of pore sizes in the soil is equally important. Soil pores can be classed as macropores, micropores and hygroscopic pores. Macropores, or air filled porosity, refer to the volume of pores which are sufficiently large for water to move freely under the force of gravity. They are important in maintaining adequate oxygen levels in the soil. If air filled porosity falls below about ten percent, then movement of air and water through the soil is restricted, and significant reductions in plant growth can occur (DeYoe 1982). Air filled porosity is closely related to soil texture and structure. For example, sandy soils have a naturally high air filled porosity while that of clay soils is often low, and most of the macropores occur as structural voids, root channels and burrows of soil animals and microfauna.

Micropores refer to those pores which can retain water against the force of gravity. The water held in micropores is still available for plant growth. The volume of micropores is a measure of the available soil water storage. Available soil water storage is

TABLE 1. ESTIMATED TOTAL POROSITY LEVELS FOR A RANGE OF SOIL BULK DENSITIES.

Bulk Density (g/cc) •	Total Porosity (percent by volume)
Mineral Soil	
1.10	58
1.30	50
1.50	42
1.70	35
1.90	27
Organic Soil	
0.02 (fibric)	99
0.20	87
0.40	73
0.60	60
0.80	47
1.00 (humic)	33

• Values listed in this table assume a maximum bulk density of 2.60 g/cc for mineral soils (Schurman and Mackintosh 1985) and 1.50 g/cc for organic soils (Hassan 1978).

lowest in sandy soils (hence their droughtiness), and highest in loam and silt loam soils. Available soil water storage in clay soils is commonly low, because clay soils have a proportionally greater volume of hygroscopic pores. Water contained in hygroscopic pores is not available for plant growth.

Effects on Soil Physical Properties

When soil is compacted, the total porosity is reduced at the expense of the macropores, i.e. pores that are drained of water at nominal field capacity under the force of gravity. Continued reduction in the volume and shape of macropores may inhibit gaseous exchange between the soil air and the atmosphere. Because micropores are relatively less affected by compaction, the proportion of micropores is increased. An increased proportion of micropores means the soil behaves as if it were of finer texture. The volumetric water content at nominal field capacity is increased, thereby increasing the volume of water per unit volume of soil that is available to tree roots (Greacen and Sands 1980).

The amount of soil compaction can be determined from soil bulk density and pore size distribution measurements. As soil compaction increases, soil bulk density increases, and this leads to a corresponding reduction in total porosity (see Table 1), which can alter water infiltration and movement through the soil, change site drainage conditions, and decrease the amount of available soil water storage.

Effects on Infiltration and Runoff

Soil compaction affects infiltration (the ability of water to enter soil) and hydraulic conductivity (the ability of water to move through the soil). Steinbrenner (1955) reported successive decreases in infiltration rate with each passage of a logging tractor over a forest soil. Also, compacted soils are often layered, with one layer being more compact and less permeable than adjacent layers.

Soil compaction can increase surface runoff because of reduced infiltration rate. However, runoff is affected by other factors besides compaction in logging operations, including the nature of surface vegetation and organic layers that intercept runoff, and the area's slope and topography. Surface water may accumulate in depressions following logging of low-lying forested sites, reducing runoff and giving localized pockets of soil having poor aeration. Because of increased strength, compacted soils have lower erodibility. For similar reasons compacted soils may be more resistant to wind erosion (Greacen and Sands 1980).

Effects on Soil Temperature

Soil temperature affects plant growth by influencing the rates of physiological processes. Soil temperature is influenced by a number of factors, including seasonal and daily variation in radiation inputs, soil moisture content, rainfall, air temperature, vegetation cover, soil texture and density. There are few forestry-related studies on the relationship between soil compaction, soil temperature and plant response.

Compaction is generally thought to increase a soil's heat conductivity and diffusion (the rates at which soil heats up or cools down), resulting in more rapid gains or losses in heat with changes in environmental conditions. This results in greater fluctuations in soil temperature, and perhaps increased depth of freezing during winter months. Organic soils have greater insulating properties than mineral soils (due to their lower heat diffusion rates), which may reduce these effects.

Effects on Soil Nutrients

Light to moderate compaction can improve nutrient flows in the soil. Plant water supply could be improved because of greater water retention and hydraulic conductivity. The uptake of mobile ions (e.g. nitrate), which mainly move in the soil by

mass flow, could be improved. The uptake of less mobile ions (e.g. phosphorus, copper and potassium), which move in the soil mainly by diffusion, could also be improved because light to moderate compaction increases the apparent diffusion coefficient of ions as well as packing more ions into a given volume of soil (Greacen and Sands 1980). However, severe compaction tends to reduce nutrient availability due to restricted root development, and more tortuous transport mechanisms within the dense soil matrix.

Influence of Organic Matter in Mineral Horizons on Compaction

The susceptibility of soils to compaction is related to its organic matter content. The more organic matter that is present in mineral horizons, the more difficult it is to compact the soil. Compaction resistance is sensitive to even small changes in organic matter content. For example, Soane (1990) reported that the addition of up to 17 percent organic matter to sandy loam and clay loam soils reduced the bulk density levels resulting from compaction by 60 percent compared to that for the same soils at three percent organic matter. For clay soils, the corresponding reduction was about 70 percent. These reductions in bulk density were not apparently influenced by the level of impact loading used in the tests.

Soil moisture interacts with organic matter content to determine compaction resistance. Organic matter increases the resistance of mineral soils to compaction more when the soil is moist than when it is dry (Soane 1990).

Compaction Characteristics of Organic Materials

Measurements of organic peat soils indicated that natural bulk density varies from 0.02 g /cc for samples of Von Post 1 (fibric) up to 0.98 g/cc for samples of Von Post 8 (humic). The fibric peat holds much of its water in a macropore network, and can be compressed more than humic, amorphous peat, which holds water in an absorbed viscous condition and shows a plastic resistance to compression similar to clay soils (Soane 1990).

Organic matter has elastic properties and will rebound after compaction. Fibric materials, including peats, will rebound more than humified materials. For example, Soane (1990) found that straw will rebound 25-45 percent following compression, while undecayed straw rebounded approximately twice as much as decayed straw.

Influence of Surface Organic Matter and Roots on Compaction

In forest soils, undecomposed organic matter accumulates on the soil surface. This surface layer, along with woody slash material and other debris on the forest floor, has the effect of protecting the surface from the effects of the heavy machinery. Johnson *et al.* (1979) found that even thin leaf litter layers had the effect of reducing compaction: the penetration resistance within the wheel track of a harvest skidder was 104 kPa in the absence of leaf cover, but only 80 kPa below a surface layer of leaf litter.

Living and, to a lesser extent, dead roots increase the strength characteristics of both mineral and organic soils (Wästerlund 1987). For example, a root mat approximately 10 cm thick in organic forest soils in North Carolina resulted in a large increase in compaction resistance with depth and probably played an important part in supporting the loads imposed by forestry vehicles (Hassan 1978). In addition, roots are an active source of organic exudates, which play an important role in stabilizing soil aggregates, thus increasing resistance to compaction and contributing to amelioration of compacted soils (Soane 1990).

2.2 Rutting

Rutting of forest soils is defined as the destruction of soil structure caused by a deformation of the soil surface. When the soil is saturated or nearly saturated, it can reach a liquid state when a force is applied. Soil rutting occurs when the downward pressure exerted on the wet soil exceeds its shear strength and causes failure. As the water content of a soil approaches saturation, compactibility decreases, because the air spaces are filled with water, but the potential for rutting increases.

In the general case, rutting is accompanied by compaction (e.g. along the sides and at the bottom of the rut), but in very wet to saturated soils, rutting can occur without compaction (Greacen and Sands 1980). Rutting may not increase bulk density because wet soil has a low air-filled porosity. However, smearing along the edges of the rut destroys soil structure, reducing the macropore space necessary for soil aeration, and reducing infiltration. A special form of rutting, called soil puddling, is the destruction of soil structure and the associated loss of macroporosity that results from repeated rutting of a soil when it is very wet. It is usually visible as "soil soup" in heavily trafficked areas.

Soil Susceptibility to Rutting

Susceptibility of forest soils to rutting is influenced by the following factors:

- applied force;
- native shear strength of the soil, which is influenced by soil structure, texture, coarse fragment content, and organic matter content;
- soil moisture levels at the time of the operation;
- season of operation;
- thickness and density of the root mat layer; and
- thickness and type (fibric versus humic) of the surface organic layer.

Rutting of soils generally occurs during the frost free season, on sites with nearly saturated to saturated mineral soils, especially those lacking a strong root mat layer. When wet, clays and silts are more prone to rutting than medium to coarse-textured soils due to their plastic characteristics at high moisture levels. Organic soils, which are composed of more than 40 cm of wet, organic material are also susceptible to rutting because of their very low load-bearing strengths. Fibric organic soils, especially those with a well-developed root mat layer, are less susceptible to rutting than well-humified organic soils. When frozen, mineral and organic soils are not susceptible to rutting.

Effects of Rutting

Rutting can affect the following soil factors:

- soil mixing;
- decrease in porosity (especially macropores);
- decrease in thickness of the root mat layer;
- decrease in surface infiltration rates;
- decrease in hydraulic conductivity;
- change in runoff rates, either increase or decrease, depending on the orientation and pattern of the ruts; and
- increased potential for erosion due to displacement of organic layers, especially when mineral soil is exposed.

Rutting will have biological effects similar to those of compaction (see previous section) but the effects are more confined to the area of the ruts. An additional effect of rutting includes altering plant communities, due to churning up soil materials, exposing buried seeds and modifying seedbeds. Concern has also been expressed that rutting may alter lateral water movement on a site, affecting surface hydrology and nutrient flow, especially on telluric sites. The effects of rutting on surface hydrology are not well understood, but it is likely that the pattern of rutting in relation to surface and sub-surface drainage pattern is important.

2.3 Soil Displacement

Soil displacement is the mechanical movement of soil or forest floor materials by equipment and movement of logs. It involves excavation, scalping, exposure of underlying material and burial of surface soils (BC Ministry of Forests 1997). The effects range from beneficial to detrimental, depending on site factors (e.g. mineral or organic soil characteristics).

Three aspects of soil displacement can produce negative effects:

- exposure of unfavorable subsoils, creating unfavorable conditions for the germination and establishment of desirable species; or favorable conditions for undesirable species;
- exposure of mineral soils sensitive to erosion; and
- redistribution of soil materials resulting in loss of nutrients.

In the Ontario Clay Belt, it has long been recognized that exposure of clay mineral soils is undesirable for regeneration of conifers. Clay soils tend to dessicate and harden when exposed to sun and air, leading to seedling survival problems related to frost heaving, dessication, and poor root penetration. Consequently, most management practices in the Clay Belt that are aimed at conifer regeneration have an objective of preserving the surface organic layer on clay soils. In some cases, where regeneration of aspen is an objective, disturbance leading to exposure of clay soils may provide receptive seedbeds.

On organic soils, disturbance that leads to the exposure of underlying, well-humified layers can result in regeneration problems, such as increased risk of frost heaving, and increased competition resulting from the exposure of buried seeds, especially grasses and sedges. However, removal of a small portion of the living *Sphagnum* moss and the surface fibric organic layers, using site preparation techniques such as shearblading, may be beneficial. McEwen (1965) noted that rapid *Sphagnum* growth following disturbance on organic sites can inhibit the establishment and growth of black spruce seedlings and layers. Shearblading will temporarily inhibit *Sphagnum* growth, allowing trees to become established.

Erosion of clay or organic soils is not considered to be a significant concern (Archibald *et al.* 1997). Clay soils are inherently strong when dry, and are thus less susceptible to erosion than other mineral soils, unless they occur on slopes, and are exposed under wet conditions. Slope gradients in the Clay Belt, especially on low-lying moist soils and organic soils, are gentle, which reduces the potential for erosion. On slopes, risk of erosion to clay soils can be minimized by preserving the surface organic layers.

Nutrient concerns related to soil disturbance are related to potential nutrient losses resulting from the removal or redistribution of soil materials, the rate of replacement of these losses, and the effect on site productivity over time. These relationships are acknowledged to be complex and are not entirely understood (Archibald *et al.* 1997). In the Clay Belt, harvesting and silvicultural practices that preserve organic layers will minimize any negative effects. Examples include the use of high flotation equipment, winter harvesting on frozen ground, and site preparation techniques that are aimed at slash redistribution rather than soil removal or mixing.

3.0 Equipment Factors

3.1 Engineering Considerations

Trafficability is the capacity of a soil to withstand traffic of wheeled and tracked vehicles. Trafficability depends on soil with sufficient bearing capacity to support vehicles and enough traction capacity to provide the necessary forward thrust. The bearing capacity of the soil is a function of the shearing strength and is attributed to friction

and cohesion between soil particles (Helvey and Kochenderfer 1990). Generally, clay soils, when dry, have higher trafficability ratings than other textures since they are denser in their natural state, and have higher shear strength due to smaller particle size. All soils become less trafficable when moist.

Machine weight, track or tire design (e.g. footprint, lugs, tire pressure, etc.) and soil water content at the time of traffic are some of the factors that determine the amount of soil compaction and resulting changes in the plant root environment, but several other factors such as vehicle speed, the number of passes, wheel slip, and recent soil loosening are also of importance (Jakobsen and Dexter 1989).

In a study of the effects of harvesting operations in Sierra Nevada forests, Miles *et al.* (1981) concluded that two components of the machine-load system had the greatest influence on soil compaction, the ground pressure of the machine, and the shear force required for turning. The shear force required to move the machine, the weight of the load transferred to the machine, and the weight and drag of the logs on the soil surface appeared to have less effect.

Wheel slip from forest vehicles contributes to compaction by generating pressures in the soil considerably greater than nominal contact pressures, depending on tire geometry and the nature of the operation. For example, pressures in the soil of up to five times the nominal contact pressures have been recorded under the back wheels of agricultural tractors (Cohron 1971). Compaction produced by wheeled skidding operations differs considerably from that expected from tractors driven across a uniform soil surface in agriculture, since the ground is uneven and causes peak loadings which greatly exceed predicted average loads (Miles 1978). Tracked vehicles are not subject to wheel slip.

Mellgren and Heidersdorf (1984) note that on soils with low shear strength, the use of a differential lock (no-spin) may increase ground disturbance and decrease wheeled skidder performance when turning due to increased transmission of shear stress. They recommend manual differential locks that can be activated when necessary for operating in these conditions.

In logging operations one axle (usually the rear) often supports a much higher load than the other. In a forwarder most of the weight of the logs is carried by the back axle, and contact pressures may be reduced by using a bogie. In addition, shear stress is generated by the moving tire or tread and is greatly added to by any pushing and pulling activities of the logging vehicle (Greacen and Sands 1980).

Dexter and Turner (1974) compared the change in compaction with time of undisturbed samples of two soils, when the external pressure was increased suddenly from 30 kPa to 1000 kPa. The authors suggest that soils with compression half-times greater than 100 seconds might be less susceptible to compaction due to machine traffic, given typical loading times of 0.5 second for tractor tires. The compression half-time (the time for half the volume change to occur towards the final equilibrium volume) for a clay soil was about 200 seconds. The use of high flotation equipment generally reduces the amount of time during which force is applied due to the possibility of higher travel speeds, reduced wheel slippage, and less likelihood of sinkage (and thus fewer times needed to manoeuvre to extract the vehicle).

While pressures from the wheels are concentrated in the soil immediately under the tread, they can be detected at considerable depth in the profile with very heavy loads. Dandfors (1974) measured soil compaction under 16 ton loads at 50-60 cm depth that still remained after three years. He concluded that with heavy loads, it is largely the load and not the contact pressure that is decisive for the magnitude of the stress at depths greater than 40 cm. Above this depth a considerable decrease in stress is obtained using equipment with a low surface pressure.

Wheel rut formation provides larger soil-tire contact area and lower contact pressure, resulting in less increase in soil density. However, this effect

diminishes with repeated traffic, and the tire inflation pressure becomes the most influential parameter (Jakobsen and Dexter 1989).

3.2 Effects of Machine Traffic on Soil Properties

The effects of machine traffic on forest soil properties are difficult to generalize due to the variability in soil and site conditions encountered in most trials. Most studies that attempted to quantify the relationship between applied stresses and compaction effects were done under laboratory conditions, which are difficult to replicate in the field. Also, some earlier studies did not adequately document equipment characteristics and other operational factors, such as number of equipment passes, and soil moisture conditions at the time of the harvest operation. As a result, in attempting to quantify machine characteristics in relation to different soil or site types, there are many information gaps. To indicate general trends, the results from several relevant studies are summarized below.

Donnelly *et al.* (1991) studied the effects of timber harvesting on a stony loam soil in Vermont with two equipment combinations: clear cutting followed by skidding with a Timberjack 380, and full tree logging with a Liebherr R925 tracked feller-buncher followed by skidding with a John Deere 640 grapple skidder. In the first case, average soil bulk density increased from 0.82 to 0.91 g/cc (an 11 percent increase) following the operation, while in the second case, average bulk density increased to 0.96 g/cc (a 17 percent increase). The authors reported no changes in soil oxygen levels following either treatment. Soil temperatures following the harvest operations were slightly colder in winter and slightly warmer in summer than control sites, but the effect of increased soil density could not be distinguished from that of removal of the vegetation cover. Since temperatures normalized within two years as the vegetation cover was reestablished, it was assumed that canopy removal was the main causal factor.

A study conducted on the Atlantic coastal plain (Hatchell *et al.* 1970) on a clay loam soil found that traffic caused a very sharp increase in bulk density of surface soils after one or two trips and a more gradual increase in density as the number of trips increased. The increase in density was greater in loamy sand or sandy loam than in clay loam or clay. This finding may have resulted from fine-textured soils having nearly saturated pores when wet and an extremely hard and cohesive condition when dry, thus resisting density changes in either extreme. Trips on wet soil did not materially increase final densities but did cause greater reduction in aeration porosity and infiltration rates.

The equipment used was a crawler tractor with 10 psi rated ground pressure hauling a loaded trailer exerting 46 psi ground pressure. Measurements taken after nine trips in a controlled trial showed a 30 percent increase in bulk density (from 0.9 to 1.2 g/cc) and a reduction in macropore space from 26 to 13.5 percent. Measurements taken on the harvested site showed greater effects on primary skid trails compared to secondary skid trails: average bulk density increases of 44 percent compared with 23 percent, total porosity decreases of 15 percent compared with 11 percent, and infiltration rate decreases of 89 percent compared with 78 percent, on the primary and secondary skid trails respectively (Hatchell *et al.* 1970).

A study to evaluate the effects of wide-tire skidder traffic (John Deere 640 equipped with Firestone 73x44-32 tires, inflated to 19 psi pressure) on loamy sand to sandy clay loam soils on Vancouver Island (Rollerson 1990) drew the following conclusions. In general, soil bulk densities increased with increasing skidder traffic (the trials examined traffic ranging from five to 80 passes both empty and loaded), as did rutting and exposed mineral soil. These effects were more pronounced at higher soil water contents. Soil texture seemed to make little difference. Most of the increase in bulk density was achieved in the first ten to 20 trips; after 20 trips, little further increase in bulk density occurred. Bulk density increases were generally in the range of five to 20

percent. The compactive effect of the wide-tire skidder was at the low end of the range of reported effects. Where rutting occurred, average depths on dry soils were from 6 to 10 cm, and on moist soils, from 15 to 30 cm.

In a study of the establishment and growth of loblolly pine seedlings on compacted soils, Foil and Ralston (1967) applied forces of 50 to 150 psi for short durations in laboratory conditions. On clay soils, they measured bulk density increases from nine to 13 percent for applied forces of 50 to 150 psi respectively. There were no changes in total porosity (which averaged about 50 percent) but non-capillary pore space was reduced from about eight to three percent in all cases. These figures are surprising given that even in its natural state this clay soil had very low macro/meso pore space, i.e. at a level thought to be limiting to root growth.

Miles *et al.* (1981) studied soil compaction effects of logging on a sandy to silty loam in California. Treatments included one to five passes of a skidder or tractor (approximate ground pressure 58 kPa) hauling a 900 kg load or a load of logs. They noted bulk density increases of 15 percent (dry soil) to 20 percent (moist soil) for the tracked vehicle; 20 percent (dry soil) to 35 percent (moist soil) for the rubber-tired vehicle; and two percent (at 25cm soil depth) to seven percent (at 15 cm soil depth) under the logs. They concluded that soil compaction is more sensitive to moisture content than any other variable. They found that soil density increased with the number of trips but much of the compaction occurred on the first trip; and that most compaction beneath the tracks or wheels of the machine was due to the weight of the machine and the shear force required to skid the turn.

Froehlich (1979a) examined the effects of logging using large crawler tractors (no specifications supplied) on a shallow (60 cm), sandy clay loam soil on a low site class ponderosa pine site in Oregon. He found bulk density increases averaging 18 percent in the upper 20 cm of the soil profiles. Bulk density increases in the 20-30 cm range were less than 10 percent.

In a preliminary study, harvesting effects on soil properties in Ontario's Clay Belt, Schurman and Mackintosh (1985) found a wide range in changes to soil properties resulting from harvesting: increases in bulk density ranging from 11 to 43 percent, and decreases in soil macroporosity ranging from nine to 68 percent. Harvesting with skidders equipped with high-flotation tires had less effect on soil bulk density and macroporosity levels, compared with areas harvested with skidders equipped with conventional, narrow tires. On the most severely affected areas, macroporosity values measured in the Ae horizon (in the upper 10 cm of soil) were less than ten percent, a condition usually considered detrimental to plant growth (Shurman and Mackintosh 1985). They surmised that with increasing vehicular traffic, total porosity and percent of macropores decreased significantly while the amount of micropores and capillary pores remained relatively constant.

Soil bulk density measurements made after mechanized harvesting in spruce-fir forests in north-central Maine indicated that compaction was greatest in the upper 10 cm of mineral soil (Holman *et al.* 1978). A study of the effect of mechanized harvesting on organic soils in North Carolina (Hassan 1978), showed that the root mat layer (contained mostly in the upper 10 cm of organic soil) was compressed by 65 percent, indicating that this layer acted as a mat and supported most of the vehicle weight. Bulk density of the organic soil to a depth of 15 cm increased by more than 50 percent, while lower zones were not greatly affected by the forest harvest and machine traffic. The author estimated that the 10 cm thick surface root mat zone increased the overall machine support (bearing capacity) of the organic soil by a factor of three. He noted that intensive site preparation practices would destroy this root mat layer, resulting in a loss in the ground support for future machine traffic and operations.

The following conclusions can be drawn from these studies:

- soil compaction effects are most evident in the uppermost 20 cm of mineral soils under

forces applied by typical harvesting practices;

- soil texture interacts with the moisture condition of the soil at the time of operation, affecting the degree of compaction;
- moist, fine (plastic) soils are more susceptible to compaction than dry, coarse soils;
- on moist, medium to fine textured mineral soils, compaction effects increase with the number of vehicle trips;
- on dry mineral soils, little compaction will result from one or two vehicle passes; and
- surface root mats, woody debris, and surface vegetation are critical in enhancing the ground strength of mineral and organic soils.

4.0 Effects on Growth and Yield

Soil disturbance influences forest growth and yield by affecting seed germination, seedling survival and establishment, and root growth. When forest soils are compacted, the environment in which the roots of vegetation exist becomes altered. There is usually a decrease in macroporosity, which can affect the penetrability of roots, decrease the amount of infiltration and hydraulic conductivity, thereby restricting water and nutrient availability, and decrease aeration of the soils, thereby affecting oxygen availability and temperature of the soil (Deyoe 1982). In some cases, light compaction can benefit tree growth by improving nutrient availability (Greacen and Sands 1980).

Our ability to confidently predict the likely effects of soil compaction on plant growth is hindered by the numerous interactions which occur following compaction of a soil. Factors limiting root growth are obviously complex and any one of a number of soil physical properties may restrict root growth (Eavis 1972). Another confounding factor is the possibility that if Clay Belt soils are naturally compact in nature, due to their mode of deposition and other environmental factors, they may be more resistant to further compaction, then the literature from other jurisdictions woudl suggest. Generalized soil compaction models that are based primarily on the effect of soil moisture on compaction characteristics may not perform well on strongly structured Ontario soils with variable dry bulk densities that are naturally compact (Veenhof and MacBride 1996).

Rutting of forest soils also affects vegetation establishment and growth. The seedbed can become altered as a result of soil mixing. The rooting environment is also affected by rutting. A decrease in macroporosity restricts the aeration and infiltration of the rooting environment. The breakdown in structure and soil mixing can expose roots and alter their strength and ability to carry out their function. Reductions in seed germination can lead to decreased natural regeneration while reductions in root function can lead to mortality or to decreases in long-term growth and yield. Table 2 summarizes the status of various soil factors in severely disturbed conditions and their possible negative effects on plant growth mechanisms.

There is a great deal of uncertainty concerning the effects of soil disturbance on forest site productivity, growth and yield. This is due to the lack of long-term growth studies, the complicating effects of previous management operations in retrospective studies, the complexity of the interacting factors operating during and after soil disturbance, and the uncertainty surrounding the ameliorative effects of various ecological factors.

4.1 Soil Factors - Thresholds

It is known that the dry bulk density at which soil strength seriously impedes root growth due to mechanical resistance depends on the soil type (Veenhof and MacBride 1996). There appears to be an optimal bulk density, or range in bulk density, above and below which a decrease in plant yield occurs. Schurman and Mackintosh (1985) suggest that for optimal plant growth, the bulk density of

mineral soils should range from 1.10 to 1.40 g/cc

Critically low oxygen levels cause a decrease in aerobic respiration while initiating anaerobic respiration. The resulting reduced energy production and toxic byproducts of anaerobic respiration reduces root elongation and root growth. It is known from experiences in agriculture that once total porosity of surface soils falls below about 40 percent, crop yield (or biomass production) declines correspondingly. Root growth of forest trees may be limited at ten to 25 percent air filled porosity (Greacen and Sands 1980). However, plant responses vary, and there is no specific information for boreal species.

Roots must overcome the strength of the soil to penetrate pores of smaller diameters than themselves. Because compaction both increases soil strength and decreases the number of macropores, the rate of root elongation and therefore root length is reduced. If the total root mass is reduced on compacted soils, there may be an effect on windfirmness, although no studies on this topic exist.

Relationships between root growth and soil strength are largely unknown for forest tree species. There are known to be differences in root penetration capabilities between tree species. For example, in greenhouse studies of seedling development, Armson and Shea (1970) showed that black spruce is capable of unrestricted root development on a broader range of soil textures than jack pine.

Soil compaction on sites in the field typically shows considerable spatial variability both

TABLE 2. POTENTIAL NEGATIVE EFFECTS OF SEVERE COMPACTION ON ROOT GROWTH OF FOREST TREES. (DEVOE 1982)

Factor	Status in compacted soil	Potential effects
Oxygen	decreased availability	decrease or cessation of aerobic respiration; anaerobic respiration results in toxin production
Water	decreased percent water content, availability usually reduced, occasionally enhanced	mechanism for nutrient acquisition disrupted, reduced cell growth, cell dessication
Nutrients	increased diffusion rates of most ions; mineralization of nutrients from organic matter decreased	reduced nutrient availability, reduced efficiency of osmotic adjustment, specific nutrient deficiences
Temperature	thermal conductivity and diffusivity increased, leading to greater variations in soil temperature	growth decreases as temperature declines below or increases above optima for cellular reations
Soil structure	strength increased; porosity decreased	exerts physical resistance to root penetration; affects oxygen, water and nutrient availability

vertically and horizontally. Roots will preferentially penetrate pockets of lower strength and structural weaknesses such as fissures and interfaces between structural units. Roots may be able to penetrate a layer of increased mean strength without serious growth loss if there are sufficient zones of weakness in the layer (Greacen and Sands 1980). Also, certain conditions may reduce the resistance of these compact layers temporarily and allow roots to penetrate them (e.g. high moisture levels during and shortly after rainstorms). New roots will also take advantage of the space created by the decay of existing root systems.

Root elongation will not occur if insufficient water is available. The critical level is the permanent wilting point. If a large volume of roots are affected, the decreasing ratio of water absorption to transpiration will induce the tree to shift from a growth to a survival (no growth) mode more quickly, resulting in a shorter period of growth over the growing season.

Hydrostatic (turgor) pressure within the elongating portion of the root generates the force needed to push the root cap through the soil. If the hydrostatic pressure is insufficient to overcome the soil penetration resistance (impedance and root/soil friction), the growing tip will be diverted in a direction of less resistance, or, if this is not possible, elongation of the root tip will cease. If a root tip aborts, the tree will attempt to develop lateral roots. Therefore, trees established in compacted soils may be able to compensate by diverting their root systems into adjacent, less affected areas.

Seed germination and seedling emergence may be adversely affected by soil compaction (Greacen and Sands 1980). Reduced oxygen and moisture levels in compacted soils have also been shown to reduce the amount of mycorrhiza associated with tree roots, resulting in less efficiency in nutrient mobilization and uptake.

4.2 Magnitude of Growth and Yield Effects

Research studies indicate that soil compaction has a measurable effect on forest growth and yield. A review of 142 studies of forest yield responses to soil compaction that were conducted between 1970 and 1977 showed that significant decreases in growth and yield were reported in 117 (82 percent) of these studies (Deyoe 1982). In a review of fourteen studies on soil compaction effects, the magnitude of reported forest growth reductions varied from five to 50 percent (Froehlich 1982).

Emmingham (1982) summarized research on the effects of compaction on seedling and tree growth. He notes the differences between measurable effects on individual trees and on stands. The effect on a stand is a function of the number of trees affected and the intensity of the impact. Differences in individual tree responses were due to the lack of uniformity of traffic and compaction over an area in contrast to compaction due to agricultural vehicles which tends to uniformly compact an area.

Froehlich (1982) reported that trees with 10 to 40 percent of their rooting zone compacted by a factor of ten percent or more above undisturbed density produced 14 percent less basal area growth over 12 years. Trees with more than 40 percent of their rooting zone compacted by a factor of ten percent or more averaged 30 percent less basal area growth. When applied over the entire harvest area, overall basal area growth reduction in the stand was estimated at ten percent.

Froehlich (1979b) indicated that growth studies in Oregon show that tree growth reductions as a result of soil compaction vary from five to over 50 percent, with the highest reductions occurring on highly-travelled skid trails and roads. Froehlich postulated that overall stand growth reductions resulting from compactive effects on a typical harvested area in Oregon would be in the order of

seven to eight percent. A study in Maine found that the impact from ground-based equipment reduced growth in young spruce-fir stands by nine to 11 percent (Holman *et al.* 1978). Maximum impacts were associated with the area immediately adjacent to skid trails, and the effects were sharply reduced a few metres from the trails.

In a study of loblolly pine seedling growth on the coastal plain (Hatchell *et al.* 1970), on different areas of disturbance (primary, secondary skid trails, and log landings), shoot growth of naturally regenerated loblolly pine was retarded on all degrees of disturbed soil during the first two years. Reduced stocking and retarded height growth were observed on primary skid trails, and detrimental effects were particularly severe on finer-textured soil.

Dry shoot weight was positively correlated with non-capillary porosity and negatively correlated with bulk density (in the 0-5 cm soil depth range). Significant interaction of these two variables suggested that poor aeration may have been the primary limiting factor, but growth may also have been affected by mechanical resistance to root extension at high bulk densities and by the interaction of mechanical resistance and aeration (which is a problem when severe compaction is coupled with excessive soil moisture). Seedlings collected from ruts formed by wheels and tracks of tractors were much lighter in weight than seedlings from the middle of trails over which logs had been drawn. Puddling of fine-textured soil also reduced germination and increased the mortality of the seedlings (Hatchell *et al.* 1970).

Wert and Thomas (1981) reported on the growth of douglas-fir in Oregon on a site logged 32 years earlier. Growth reductions in the skid roads and transition zones resulted in an overall volume loss of 11.8 percent for the total area. Trees growing in the skid roads took 4.1 years longer to reach breast height than those growing in the undisturbed areas.

In a study of loblolly pine grown on core samples of soils which were compacted, Foil and Ralston (1967) found that seed germination was not affected by soil type but seedlings became established with difficulty on clay cores and on heavily compacted cores of lighter texture. In a study of compaction by forestry equipment on four soils in the Alberta foothills, Corns (1988) found significant reductions in seedling growth and survival associated with increasing bulk densities, at levels approximating those observed immediately after, and five to ten years after logging and site preparation.

Several authors noted the difficulty in predicting the effect of soil compaction on tree and stand growth in the field because of the complex interactions involved. For example, an increase in soil strength following compaction may result in trees with more compact root systems occupying less volume of soil. However, if air, water, and nutrients are in plentiful supply, and root length is sufficient to meet the requirements of the shoot, then top growth need not be impaired as a result of the restricted root system. Under these circumstances compaction may even be beneficial. Plant water supply could be improved because of greater water retention and hydraulic conductivity. The uptake of mobile ions (e.g. nitrate), which mainly move in the soil by mass flow, could be improved. The uptake of less mobile ions (e.g. phosphorus, copper and potassium), which move in the soil mainly by diffusion, could also be improved because light to moderate compaction increases the apparent diffusion coefficient of ions as well as packing more ions into a given volume of soil (Greacen and Sands 1980).

Froehlich (1982) reported that although growth reductions have been documented both in the laboratory and in the field, more research is needed to quantify the effects of compaction on growth over the wide array of soil and climatic conditions and over time. Due to the specific nature of the soil and climatic factors affecting both tree growth, and the recovery of soils from compaction effects, it is very difficult to predict how much and for how long an increase in soil density will affect tree growth on a specific site. Also, in any study on residual stand response, the adverse effects observed on growth of residual trees may include the effects of other

factors as well as those of soil compaction, such as direct damage to roots. Also, the spatial distribution of compaction over an area, which is a function of harvest method and pattern, must be considered when evaluating potential growth reductions.

5.0 Longevity of Soil Disturbance Effects

5.1 Soil Improvement Factors

Natural mechanisms for ameliorating the effects of soil compaction and rutting include soil shrinkage and swelling induced by freeze-thaw and wetting and drying cycles, the formation of soil gaps and pores caused by the development of ice lenses, the soil mixing action of soil fauna, and penetration by plant roots. The extent to which compacted soil will recover depends on the soil type and the degree of compaction. Clay soils, which swell and shrink, may recover, or partly so, with subsequent freezing and thawing, and wetting and drying. Recovery from compaction in sandy soils is slower (Greacen and Sands 1980).

Freeze/thaw is considered to be responsible for the formation of macropores in forest soils. Freezing the soil increases its porosity because the growth of ice crystals causes displacement and bulking of the soil. The formation of ice in soil pores may cause soil deformation and changes in density. Soil deformation is likely to occur in fine-textured soils upon freezing due to the formation of ice lenses. The action of frost on clay soils can cause clods and compact layers to be broken down to form finely-aggregated soil or frost tilth. On freezing a moist soil, ice crystals generally form a succession of layers of ice or ice lenses with a partial drying of neighbouring soil (Miller 1980).

Freezing and thawing was thought by many in the 1950s and 1960s to ameliorate compaction of the clay soils in the U.S. corn belt. With the advent of large farm machinery, however, compaction persists despite annual freezing and thawing. More than a decade may be needed to alleviate subsoil compaction as reported by several investigators.

Field experiments show that the bulk density decreases as compacted soils freeze. As the frozen soils thaw, however, the soil reconsolidates with no apparent lasting change in density (Brown and Payne 1990a, 1990b). Kay (1990) looked at the significance of ground freezing on soil bulk density under different tillage regimes on agricultural soils. Bulk densities subsequent to thawing on zero till plots returned to values that existed prior to freezing, while for plowed plots, bulk density after thawing was lower than before freezing and plowing. This is because the spaces created by ice lenses are unstable and tend to collapse on thawing unless structural changes in the soil also occur, in this case by ploughing.

Accompanying any permanent change in soil density must be a change in soil structure or aggregation. The length of time needed for these structural changes to occur naturally in clay soil is not known, but it is thought to be a long-term process requiring time ranging from decades up to 100 years (Voorhees and Sharratt 1997). Richer, warmer sites probably recover more quickly than poor, cool sites due to increased abundance and activity of soil fauna. The re-establishment of vegetation on a site is also likely a factor in the recovery rate due to the ameliorative effects of plant rooting, although there are no specific studies related to these factors.

5.2 Soil Recovery Rates

The general trend in the literature with regard to the recovery of soils from compactive effects of harvesting operations is that the time required for mineral soils to return to pre-harvest conditions is on the order of five to ten years for well-drained clayey soils, and ten to 20 years for poorly drained clayey soils. However, some authors indicate that under certain conditions, the time required for recovery may be longer. One difficulty in

understanding the time needed for recovery of compacted soils is the limited understanding of the relationship between changes in soil physical properties on growth and yield over the long term. The results of several relevant studies are summarized below.

In a study of the effects of harvest operations on soil properties in spruce-fir forests in central Maine, bulk densities returned to pre-harvest levels in random cut areas after one year; in skid trails in winter harvested areas after two years; but in skid trails in summer harvested areas, bulk densities had not returned to pre-harvest levels after three years. Depth of organic matter decreased along skid trails after harvesting, but returned to pre-harvest levels after three years on winter cut areas, but not on summer cut areas. It was concluded that soil disturbance effects resulting from winter harvesting were small in magnitude and of short duration; while the effects from summer harvesting were greater in magnitude and more persistent (Holman *et al.* 1978).

In a study of compaction by forestry equipment on four soils in the Alberta foothills, Corns (1988) found that soil bulk densities on clay and clay loam soils on the clear cut areas had recovered to the same levels as the controls, at comparable depths, at ages ranging from zero to 21 years.

A study of the effects of harvesting operations in upland hardwood forests in Vermont (Donnelly *et al.* 1991) found that bulk density recovery periods varied from two years on a stony till to 16 years on a severely compacted roadway on a sandy loam. Overall, these bulk density increases resulting from the harvest operations were relatively small and did not significantly affect soil oxygen levels.

A study on the Atlantic coastal plain did not detect any trends toward partial recovery of compacted soils after one year, for textures ranging from loamy sands to clay loams. Severely disturbed soils logged at various times over a 19 year period did recover slowly. The average time required for bulk density on log landings to return to the bulk density of undisturbed soils was estimated to be 18 years; it was estimated that 40 years would be necessary for full recovery of infiltration capacity on an severely compacted old forest road (Hatchell *et al.* 1970).

Ivanov (1976) found logging of spruce forests caused compaction and that the time for the original bulk density to be restored was five to seven years for well-drained soils and approximately 15 years for poorly drained soils. Dickerson (1976) estimated that recovery of wheel-rutted and log-disturbed soils would take about eight years following tree-length skidding on silty clay loam soils.

Groot (1996) found that on study areas on organic soils in the Ontario Clay Belt that had been rutted by harvest operations, rapid invasion of vegetation (including Sphagnum mosses, grasses and sedges) into the ruts occurred. Even on deeply rutted sites, the rut cover decreased rapidly, and significant differences among harvest treatments could not be discerned after six years.

6.0 Forest Soil Management and Mitigation

6.1 Management Considerations

The degree and type of soil disturbance is dependent on the nature of the downward force on the forest floor. These forces vary with the type of management practices being utilized. For example, careful logging conducted on frozen ground or in the frost-free period using high-floatation equipment reduces ground disturbance, preserves seedbeds, and reduces rutting and compaction. The following management factors affect the degree of soil disturbance:

- harvesting system and logging system
- equipment (ground pressure, number of passes)
- skid road spacing, pattern and gradient
- site preparation type pattern, depth of scalping

- prime mover implement
- slope gradient (adverse, favorable)
- operator experience, and instructions
- seasonal soil moisture content
- extent of ground freezing
- compressibility/depth of snow.

The type of equipment used for forestry operations determines the ground pressure exerted on the forest floor. As a result different types of equipment used in conjunction with different management techniques can result in varying degrees of forest soil disturbance. It is therefore important to match harvesting equipment to the site and season in order to reduce soil disturbance. For example, larger equipment such as clambunk skidders reduce the number of trips and skidways required for harvesting. However, sites with low ground strength would receive significant disturbance due to the higher ground pressures exerted by these machines and loads, unless they are equipped with low pressure tires or tracks.

The susceptibility of forest soils to compaction or rutting is influenced by a number of factors, including the depth and nature of the surface litter, soil organic matter content, soil texture, soil structure and soil moisture levels. The degree of compaction or rutting is also affected by the amount and type of pressure applied by the equipment, and the number of passes over a given area (repeated passes have a cumulative effect). For example, clay soils are more susceptible to compaction when wet than when dry; repeated passes of a skidder over on area increases the amount of compaction and/or rutting; and high flotation forwarding equipment reduces the pressure exerted on a soil as compared to conventional narrow-tired forwarders, and therefore, reduces the potential for compaction and rutting.

Groot (1987) rated the degree of site damage during forest harvesting on peatlands according to site type and harvesting method. During the frost-free season, susceptibility to damage increases from operational groups (Jones *et al.* 1983) 11 (Labrador-tea), to 12 (Alder-herb poor), to 13 (Alder-herb rich). Winter harvesting produces the least amount of damage, but damage can occur during portions of the winter when frost has not penetrated deeply into the ground and snow cover is not deep.

6.2 Identifying Soil Disturbance in the Field

A variety of field symptoms can help to identify compaction as a potential problem. Soil conditions include standing water in pools and other visible drainage problems related to reduced water infiltration. Plant symptoms include fewer roots in the soil profile, shallower or constricted roots, slow emergence of vegetation in the spring, uneven growth, signs of nutrient deficiencies, and signs of early drought symptoms (Wollenhaupt 1985).

Field tools such as pocket penetrometers and Torvane gauges are easy and practical to apply in the field to compare soil properties (penetration resistance and shear strength, respectively) on disturbed conditions with adjacent undisturbed sites. More rigorous sampling of disturbed soils (e.g. bulk density sampling) is more difficult, can be expensive to process, and may require large sample sizes due to inherent variations on the site.

Visual assessments of the extent and distribution of soil displacement and rutting can be used to infer disturbance levels, but caution must be employed: if evaluated during wet periods, rutting can appear to be more extensive than under normal conditions.

6.3 Techniques for Prevention and Amelioration

Mitigation of soil disturbance effects is best focused on prevention rather than treatment. In managing natural soil factors, the maintenance of organic matter in forest soils should be a long-term management aim (Greacen and Sands 1980).

Traffic control and the avoidance wherever possible of logging wet soils is probably the single most important management practice for prevention or reduction of compaction and rutting damage. Wherever possible, machines that cause less compaction should be used. Under some circumstances greater compaction of a smaller area may be preferable to less compaction of greater area. The extent and degree of compaction will depend on extraction patterns, and the resulting frequency and distribution of equipment passes.

The incidence of compaction during any traffic event also depends on the compactibility of the soil at that time. The complementary nature of both vehicle and soil factors confirms the need to consider reduction in compactibility in any attempts to overcome compaction problems. Soil moisture content at the time of operation is recognised as being one of the most important factors influencing compactibility and the need to avoid traffic on wet soils is recognised by farmers in northern temperate regions where high soil moisture is frequently encountered during spring seedbed operations as well as at harvest (Soane 1990).

To minimize compaction when skidding, Miles *et al.* (1981) recommend the following:

- confine skidding to a low density trail network (few trails instead of many);
- locate skid trails on the driest available soil;
- winch logs to the trail instead of travelling to each log;
- transfer as much of the load to the machine as possible, or carry the load off the ground (such as on a forwarder) to minimize the load on the soil; and
- use machines that have large soil contact areas and low ground pressures.

Mechanical loosening of soil through surface raking or subsoiling is an option to rehabilitate severely affected areas, such as old roads, but is too expensive to consider on a large scale. Also, these techniques may create additional problems on clayey soils due to organic matter displacement, exposure of fine-textured mineral soils, and subsequent frost-heaving and dessication.

7.0 Preliminary Ratings for Susceptibility to Compaction and Rutting for Clay Belt Soil and Site Types

The following tables provide preliminary ratings for susceptibility to compaction and rutting, for a range of soil textures and soil moisture conditions. The predicted ratings are based on the combined effects of soil compaction, and reductions in air filled porosity caused by a destruction of soil structure. The information presented in these tables is not based on Clay Belt specific research, rather, they are based on a synthesis of information gained from similar work conducted elsewhere in Ontario (McBride 1982a, 1982b; Arnup and Mackintosh 1986). As such, they should be viewed only as a first approximation. The tables provide a preliminary basis for predicting and testing the effects of various on-site operations on different soil textures and drainage regimes, at different times of year.

Table 3 provides ratings for mineral soil types (soil texture and drainage classes) according to their relative susceptibility to compaction, from least to most susceptible. The table does not reflect the actual magnitude of the changes in soil properties (such as changes in bulk density), but rather the predicted effects of these changes relative to the critical levels of soil air space required by plants for unrestricted growth. For example, although the actual percent change in total porosity in a sand may be much greater than that in a clay soil under the same applied force, the relative impact on growth in a clay can be greater, because its macroporosity is normally low.

Table 4 provides ratings for northeast soil and site types (McCarthey *et al.* 1994) according to

their predicted susceptibility to rutting, under different soil moisture regimes and seasonal moisture and frost conditions. This table has been subdivided into three seasons of operation: wet, frost-free (spring and fall); dry, frost-free (summer); and frozen (winter). The two frost-free seasons have been differentiated to allow for the very different surface drainage conditions at those times.

TABLE 3. PRELIMINARY RATINGS FOR SUSCEPTIBILITY OF MINERAL SOIL TYPES TO SOIL COMPACTION AND REDUCTIONS IN AIR FILLED POROSITY FOR THE CLAY BELT (FIRST APPROXIMATION).

	Drainage class				
Soil Texture	poor	imperfect	mod. well	well	rapid
Heavy Clay, Clay, Silty Clay Sandy Clay, Silty Clay Loam	1	1	2*	2*	na
Clay Loam, Sandy Clay Loam	1	1	2*	2*	na
Silt Loam, Loam, Silt	1	2	2*	3*	na
Sandy Loam, Loamy Sand, Sand	2	2	2	3	3

1 = most susceptible, 2 = intermediate, 3 = least susceptible
* These soils are more susceptible to compaction during wet periods, especially in spring and fall.

TABLE 4. PRELIMINARY RATINGS FOR SUSCEPTIBILITY OF SOIL TYPES TO RUTTING BY SEASON FOR THE CLAY BELT (FIRST APPROXIMATION).

Site/Soil Types Site (ST & Soil (s) Types	Spring and Fall (frost-free, wet)	Summer (frost - free, dry)	Winter (frozen)
Organic soils (more than 39 cm organic matter)			
ST 11 / S17 (fibric)	1 to 2	2 to 3	3
ST 12 / S18 (mesic)	1	1 to 2	3
ST 13 / S 19 (humic)	1	1	2* to 3
ST 8,9,10 / S15 , S16	1	2	3
Moist, poorly drained soils: ST 10 / S14, S15.	1	2	3
Fresh to moderately moist, imperfectly to well drained fine soils (clayey and fine loamy): ST 5a, 6a, 7a / S9, S10, S11, S12, S13.	1	3	3
Fresh to moderately moist, imperfectly to well drained coarse loamy soils, sandy loams and loams, silts and silt loams: ST 3a, 3b, 4, 5b, 6b, 6c, 7b / S2, S4, S5, S6, S7, S8.	1	3	3
Dry to fresh, rapidly or very rapdily drained sandy soils: ST 2a, 2b / S1, S2, S3, S4.	2	3	3

1 = most susceptible, 2 = intermediate, 3 = least susceptible.

* when not frozen due to water movement

8.0 Summary

Soil disturbance refers to a change in the natural state of a soil caused by an artificially imposed force. Forest soil disturbance can be broken down into three categories: compaction, rutting, and soil displacement. Soil compaction is the increase in soil density that results from the rearrangement of soil particles in response to applied external forces. Compaction is a process which leads to an increase in soil density as a result of the application of stresses, usually of short duration, resulting from the passage of machine traffic. Soil compaction, depending on its severity, can increase soil bulk density, decrease air-filled porosity (especially macropores), decrease infiltration rates, decrease hydraulic conductivity, increase heat conductivity and diffusion, increase depth of freezing, and change nutrient ion diffusion rates.

Soil compaction can occur on any site with any type of soil. However, it is generally more severe on sites without a root mat or surface organic matter; and on moist clays, loams and silts that are low in organic matter content. Coarse fragment content, root mats and surface organic layers reduce the susceptibility of mineral soils to compaction. Fully saturated mineral soils are less susceptible to compaction since the air spaces are filled with water under these conditions. Well-humified organic soils are more susceptible to compaction than fibric soils due to the elastic properties of fibric materials.

Rutting of forest soils involves the destruction of soil structure caused by a deformation of the soil surface. Soil rutting occurs when the downward pressure exerted on the soil exceeds its shear strength and causes failure. Rutting occurs when the soil is saturated or nearly saturated; generally, clays and silts are more susceptible than coarser mineral soils (sands and loams). Well-humified organic soils are more susceptible to rutting than fibric soils due to their lower shear strength. Coarse fragment content, root mats and surface organic layers reduce the susceptibility of mineral soils to rutting. Rutting has effects on soil properties similar to those of compaction, and can also alter surface and subsurface drainage patterns.

Soil displacement is the mechanical movement of soil or forest floor materials by equipment and movement of logs. Concerns related to soil displacement include exposure of unfavorable subsoils, soil erosion, and nutrient displacement. In the Clay Belt, appropriate forestry practices will minimize potential negative effects related to these concerns.

Machine weight, tire pressure and soil water content at the time of traffic are some of the factors that determine the amount of soil compaction and resulting changes in the plant root environment, but several other factors such as vehicle speed, the number of passes, wheel slip and recent soil loosening are also of importance. Generally, clay soils, when dry, have higher trafficability ratings than other textures since they are denser in their natural state, and have higher shear strength due to smaller particle size. All soils become less trafficable when moist.

Studies of the effects of machine traffic on soil physical properties indicate the following trends:

- soil compaction effects are most evident in the uppermost 20 cm of mineral soils under forces applied by typical harvesting practices;
- compaction effects are greatest on moist, medium to fine textured mineral soils; these effects can be minimized with appropriate forestry practices, such as using equipment with low ground pressure, and organizing the movement of equipment to reduce the number of vehicle trips;
- on dry mineral soils, little compaction will result from one or two vehicle passes; and
- surface root mats, woody debris, and surface vegetation are critical in enhancing the ground strength of both mineral and organic soils.

Research studies indicate that soil compaction has a measurable effect on forest growth and yield.

A review of 142 studies of forest yield responses to soil compaction that were conducted between 1970 and 1977 showed that significant decreases in growth and yield were reported in 117 (82 percent) of these studies (DeYoe 1982). In a review of fourteen studies on soil compaction effects, the magnitude of reported forest growth reductions varied from five to 50 percent (Froehlich 1982).

There are difficulties in predicting the effect of soil disturbance on tree and stand growth in the field because of the complex interactions involved. Although growth reductions have been documented both in the laboratory and in the field in other jurisdictions, more research is needed to quantify the effects of compaction on growth over the wide array of soil and climatic conditions and over time. Due to the specific nature of the soil and climatic factors affecting both tree growth, and the recovery of soils from soil disturbance effects, it is very difficult to predict how much and for how long changes in soil properties will affect tree growth on a specific site. Better information on baseline soil properties and on local climatic regimes in the Clay Belt will be needed to develop quantitative models.

Mechanisms for ameliorating the effects of soil compaction and rutting include soil shrinkage and swelling induced by freeze-thaw and wetting and drying cycles, the formation of soil gaps and pores caused by the development of ice lenses, the soil mixing action of soil fauna, and penetration by plant roots. The general trend in the literature with regard to the recovery of soils from compactive effects of harvesting operations is that the time required for mineral soils to return to pre-harvest conditions is on the order of five to ten years for well-drained clayey soils, and ten to 20 years for poorly drained clayey soils. However, some authors indicate that under certain conditions, the time required for recovery may be longer. One study on organic soils in the Ontario Clay Belt found that even on deeply rutted sites, rut cover decreased rapidly due to invasion of ruts by vegetation, such that significant differences among harvest treatments could not be discerned after six years (Groot 1996).

Mitigation of soil disturbance effects is best focused on prevention rather than treatment. The maintenance of surface organic matter layers on fine-textured mineral soils should be a long-term management objective. Use of equipment appropriate for site conditions, traffic control, and the avoidance wherever possible of logging on wet soil conditions are probably the most important management practices for prevention or reduction of compaction and rutting damage.

Key knowledge gaps related to the implications of soil disturbance for the Clay Belt include the effects of rutting on surface hydrology; information on the relationship between levels of soil disturbance and effects on vegetation succession, growth and yield; and information on the tolerances of different sites to equipment operations, e.g. effects of machines with different ground pressures, number of vehicle passes, etc., on soil properties, in relation to baseline conditions. Research in these areas is needed to permit the development of quantitative, locally calibrated models that are specific to Clay Belt soil and climatic conditions.

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